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Internal Heating of an IGBT Module in a System with a Regenerative AC Drive

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The purpose of this thesis was to understand the internal heating of an IGBT module inside an AC drive in a system with a regenerative unit to it.

During the implementation of the lab, various approaches were taken in an effort to collect measurements appropriate to the topic of investigation. The IGBT junction temperature was recorded over a sustained period of time at various speed of the induction motor. The braking torque applied through a second AC drive was varied in order to study the effect of a changing torque on the overall temperature of the IGBT module of the AC drive.

With the data collected, one was able to determine the thermal resistance of the IGBT module in the system for a specific speed and torque. At the conclusion of the study, the efficiency of the system was estimated for the sake of understanding the rate at which the energy entering the system was converted into useful work.

Keywords	IGBT, AC Drive, Temperature, Motor, Generator

Contents

Abbreviations

AC:	Alternating Current
DC:	Direct Current
AC-AC:	AC to AC conversion
VAC:	Alternating Current Voltage
AC Power:	Alternating Current power
IGBT:	Insulated Gate Bipolar Transistor
MOSFET:	Metal Oxide Field Effect Transistor
VGE:	Gate-Emitter Voltage
VCE:	Collector-Emitter Voltage
PWM:	Pulse Width Modulation
emf:	Electromotive force
rpm:	Revolutions per minutes

1 Introduction

1.1 Background

The traditional and conventional methods of controlling motors by means of on/off lead to considerable amount of energy waste. The demand for power semiconductors is on the constant rise. As to why they are sought after, one cannot overlook the fact that power electronic devices convert electrical of one form to another with higher efficiency, whether it is DC power to AC power or vice-versa. What is even more remarkable is their capability to handle larger power without breaking down nor becoming damaged. These features make these power electronic devices suitable for all sort of tasks and have contributed to their popularity. Often they are found in larger electromechanical system such as in electric drives, where there is a need to control the motion and the speed of a machine. Electrical drives could be seen as a tool to control the speed of an electrical motor. In the case of an induction motor, the drive achieves the outcome by converting AC of a specific frequency into one, whose frequency could be varied.
The frequency converter as a key part of an electric drive takes full advantage of power semiconductors by turning an AC of a specific frequency into a variable frequency AC. A frequency converter is made of semiconductor switches such as IGBTs, power MOSFET and alike. The use of a frequency converter in many industries is driven by the need to reduce the energy waste; since the speed could be increased or reduced to a required level at ease, as opposed to traditional means whereby a motor is ran at constant speed. In short, a frequency converter regulates the output, minimizes the losses, thereby leading to a high efficiency conversion rate. The power converters achieve lower losses since they operate as switches; in doing so, the power dissipated is maintained at minimum at all times.

Among many applications, one can cite the use of frequency converter to control the speed of an AC motor and its torque. With great demand for power converters comes the need to minimize the losses even further, as well as the need for more power handling capabilities.

1.2 Relevance of the thesis topic

As mentioned above, power semiconductors can handle large power. For such capacity, even a minimal loss represents a sizeable amount of energy. The energy dissipated is turned and then spread to the surroundings of power semiconductors. Noted also, was how the frequency converter make use of power semiconductor switches in order to convert an alternating current of a single frequency into one, whose frequency could be varied. The aim of this study is to understand the internal heating of an IGBT module, which are used in frequency converter as an inverter: for converting DC from DC bus to AC of controlled frequency, which will then be delivered to the load.

At high voltage, high power switches such as IGBT are bound to generate a certain amount of heat, incurred from power losses. When IGBT overheats, it gives rise to the junction temperature of an IGBT. The IGBT are sensitive to excessive voltage and excessive temperature. Unless by some means the heat generated is alleviated, the overheating could affect the reliability and the performance of a device, in this case an IGBT. Considering the multitude of sectors where these power semiconductors are critical, the understanding of the rise in IGBT temperature is crucial, for implementing better ways to control and manage the heat dissipated.

Currently the IGBTs are being used in various high power applications, like in electric vehicle motor drives, solar inverters, and many more household electrical appliances. Because of this it is important to discuss the rise of heat inside an IGBT module under operation. The study tries to clarify how the temperature increases and spreads across the IGBT module and how the temperature is at different points across the IGBT module

1.3 Introduction to the thesis topic

Power semiconductors generates heat during use. Heat dissipation is a very important issue when dealing with power semiconductors, since they are associated with power losses. If the components are not cooled down effectively, it could affect the reliability of their performances. For an efficient cooling methodology, it is important to understand the pattern of heat propagation in and out of the semiconductor component.

As part of power Electronics class, a new lab measurement was set to be added on the curriculum of power electronics laboratory class. The present study is some sort of test subject in which measurements and setup were assessed to see whether the lab would be feasible and implementable.

This paper looks into the heat across the inverter's IGBT modules. The question of investigation is to which extent does the IGBT as a power converter heats up. For that purpose, an experiment would be set up. This thesis seeks to understand the temperature of an IGBT module when a regenerative drive and generator are added to system of a three phrase induction motor.

2 Classroom Input and Theoretical Background

Before continuing any further in this work, a recall of topics learned in the classroom during the power electronics lectures, is crucial. This will serve as basis or foundation, if one is to comprehend major subjects discussed herein.

2.1 IGBT

IGBT stands for Insulated Gate Bipolar Transistor. An IGBT is a very popular semiconductor that combines the voltage characteristics of bipolar junction transistor such as low conduction losses, and high input impedance with the Insulate gate of a MOSFET (Metal oxide Field-effect transistor). Thereby allowing the IGBT to have lower conduction losses than a MOSFET, while having a higher switching speed than a BJT. That is mainly part of IGBT appeal in the industry, as it features quite a nice tradeoff between losses and the switching speed frequency [1, 738]. Fig1 shows a simplified circuit of an IGBT.

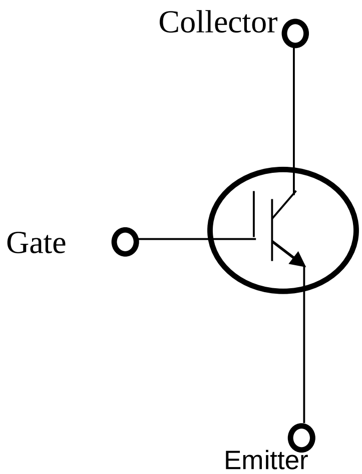

Fig1. A simplify circuit of an IGBT

The output performance of a BJT is seen by the use of PNP (collector and Emitter) while it is driven by an insulated gate from MOSFET technology. This morphology has a lot of implications. The MOSFET gate makes it so that it only requires a small voltage to start and to maintain the conduction.

a. IGBT Structure Overview

The IGBT combines the best attributes of both BJT and MOSFET, hence its popularity in high power applications. The IGBT structure is made of four alternating semiconductor layers in the order of N-P-N-P. This configuration also forms a parasitic thyristor inside the IGBT as it is shown on Fig2. The parasitic thyristor is suppressed in order for the IGBT to operate as a transistor [1, 759]. There are two types of IGBT made by manufacturers: Non-Punch through (NPT) IGBT and Punch Trough (PT) IGBT. The (PT) IGBT incorporates an N+ Buffer layer in its design whereas the (NPT) IGBT does not. Fig2 presents a basic structure of an IGBT.

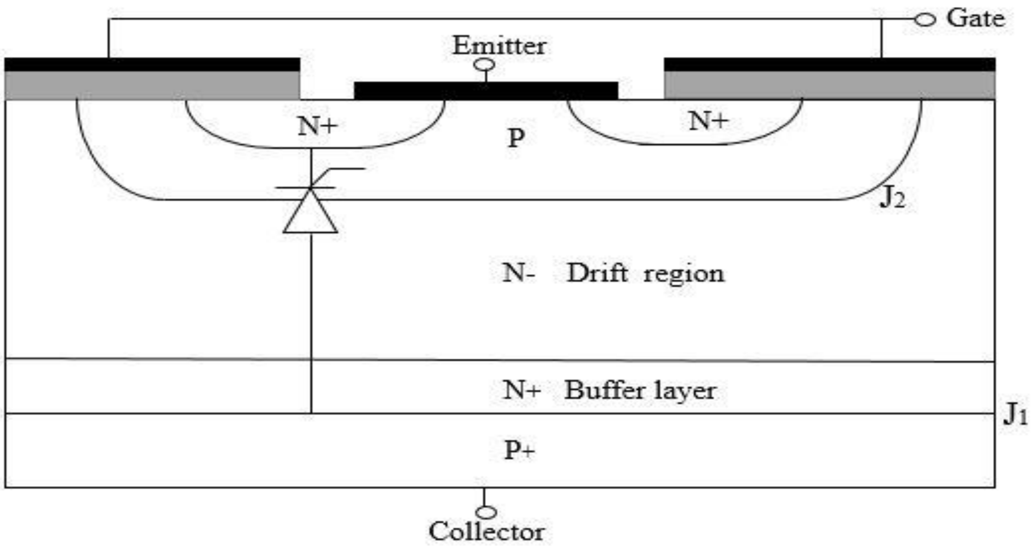

Fig2. Structure of a (PT) IGBT

The cross section of the IGBT looks similar to that of a power MOSFET except P+ layer. The presence of an N+ buffer layer as it is the case on Fig2, implies a thinner N- drift region. A thinner N-drift region minimizes the on-state voltage drop while the presence of a N+ buffer layer lower the tail current during turnoff [2, 174]. Therefore, the performance of (PT) IGBT is improved through loss reduction. Unlike a (NPT) IGBT, a (PT) IGBT has an asymmetrical voltage handling capability as it can support lesser reverse breakdown voltage.

b. Operation and Output characteristic of an IGBT

When the gate is shorted to the emitter, applying a positive voltage from the collector to the emitter results in a forward blocking mode of the IGBT. J1 on Fig2 is forward bias

whereas J2 becomes reverse biased. In this forward blocking mode, a depletion region is formed in the N-drift layer closer to J2. The depletion area permits the IGBT to block a positive voltage applied from the collector-to-emitter terminal.
On the other hand, when a negative bias is applied across the collector to emitter. The IGBT goes into reverse blocking mode. J1 is reverse biased while J2 is forward biased. The negative voltage is supported at the depletion area formed closer to J1.

The IGBT goes from forward blocking mode to forward conducting state, if a positive voltage is applied across the gate to emitter in conjunction with a positive bias applied at the collector-to-emitter terminal. When a positive voltage above the threshold is applied from the emitter to the gate terminals, a conductive channel is formed across the body region, thereby permitting the current to flow form the collector to the emitter. Fig3 high-lights the output characteristic of an IGBT

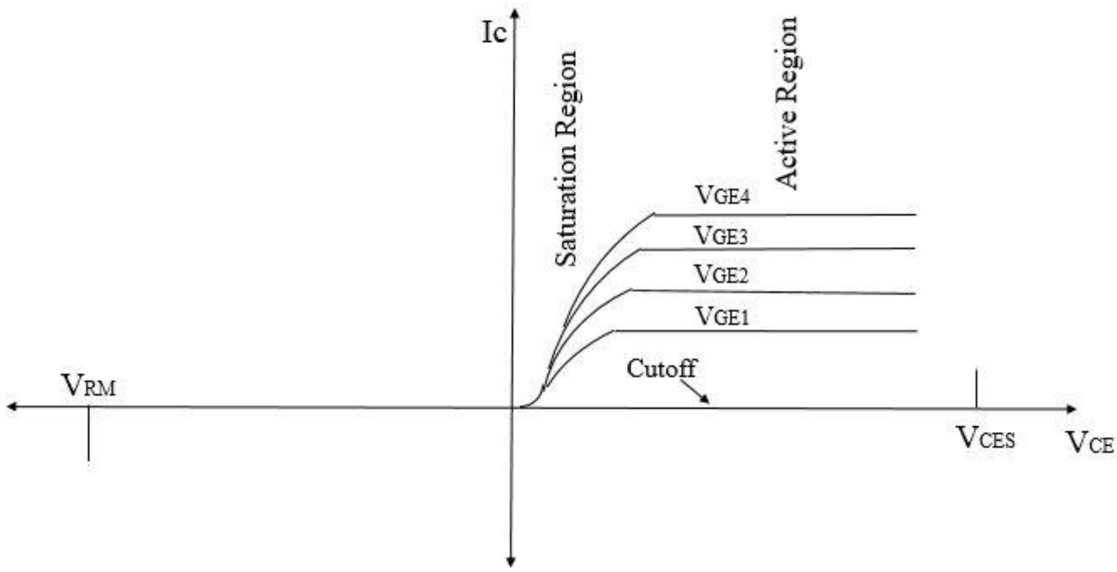

Fig3. Steady State characteristics of an IGBT

Like other transistor types, the IGBT has three operating modes. When the gate–emitter voltage (V_{GE}) is below the threshold voltage, the IGBT is said to be operating in the cutoff mode. When V_{GE} is higher than the threshold voltage, it is said to be in active mode**.** If however, the V_{GE} is increased beyond the threshold, the IGBT is said to be in saturation mode, as the V_{CE} (collector Emitter) decreases with ever increasing V_{GE}. The advantage of operating in the saturation mode is that the voltage drop across IGBT changes slightly if not constant when the V_{GE} is raised considerably. Couple that with high power handling capability, suddenly you have got yourself a good power converter. V_{RM} is the amount

of voltage that a specific IGBT is capable of blocking in reverse direction while V_{CES} represents the breakdown voltage in forward direction.
The IGBT is used in power electronic as a switch. Therefore, the IGBT is operated either in cutoff mode or in saturation mode.

c. IGBT Switching Characteristics and losses.

An IGBT is a power electronic switch. When the switch is on state, the resistance is near zero. Hence more current is being drawn as can be seen on Fig4.

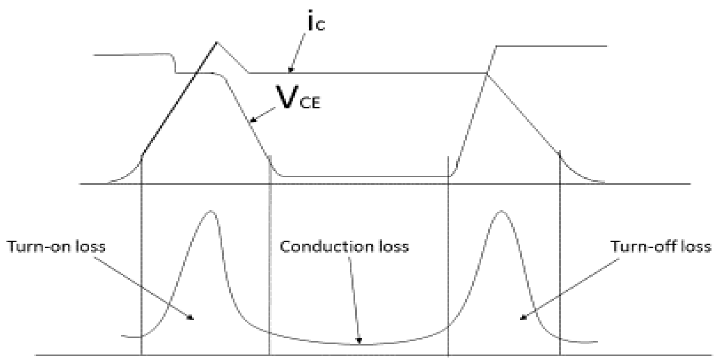

Fig4. Current and Voltage waveforms of an IGBT

Since the on-state is very low, the voltage drop is low as well. The turn-on loss is the loss by the IGBT when it is in transition from off to on state while the turn-off loss is the loss from on to off state.

d. Safe Operating Area of an IGBT

Safe Operation of Area describes the Current-Voltage limitation within which a power switching device such as an IGBT could be operated without failing. The safe operating area is of critical importance for proper utilization of an IGBT. As seen on page5, the IGBT comprises in its structure a dormant parasitic thyristor. The Safe operating Area specifies the maximum collector current that could cause a latch up of the parasitic thyristor at low collector-to-emitter bias voltage. At the low collector current levels, the safe operating area highlights a bias voltage that could result in a breakdown of the IGBT.

Forward bias safe operating area of an IGBT in inductive load application indicates the maximum collector-to-emitter voltage that is supported by the IGBT when the collector current is saturated. During turn-on of the IGBT, both holes from the P+ collector on Fig2 and the electrons from the MOSFET channel emitter are supplied into the N-drift region [1, 960]. As the whole current density is larger than the electron density, it results in net positive charge which affect the electric field distribution within the drift region as well the breakdown voltage. The breakdown voltage decreases with increasing collector current saturation.

The reverse breakdown safe operating area of an IGBT regulates that the amount of current that could be turn-off safely. When an IGBT is turn-off in inductive load application, by lowering the gate-to-emitter voltage to zero or to negative; a collector-to-emitter voltage is supported at the J2 (refer to Fig2). Due to no gate voltage, the electrons stop going into the drift region whereas the holes are very much present and keep coming through the N layer of the IGBT. As a result; the net positive charge is higher and it leads to a larger electric field at the junction J2. Since the net positive charge of an IGBT during turn-on transient is larger than at turn-off, the reverse bias safe operating area is lesser than the forward bias safe operating area.
In case of a short circuit at the inductive load, the short circuit safe operating area of an IGBT highlights its ability to handle high current and high voltage for a very short period of time before a feedback control circuit kicks in and turns the IGBT off.

2.2 Heat Transfer and Heat Management in Power Semiconductors

Heat could simply be viewed as the added warmth to an object as a result of an increase in its kinetic energy level. Heat transfer is defined by some as a transfer of kinetic energy of molecules from high temperature object to a low temperature object [3, 11].
Heat transfer mechanisms
Heat transfer involves a high temperature object, component, or substance transferring its internal energy to a low temperature object. There are three main mechanisms by which heat could be transferred between two medium.
Conduction**:** is a mechanism by which heat is exchanged between two objects of different temperatures that are close enough or in other words through direct contact.

Convection**:** is when the heat transfer towards liquid or gazes causes a circular motion within the liquid whereby warmer molecules move up (away from the source of energy) while the less warm molecules moves down toward the source of energy.
Radiation**:** is heat exchange mechanism that does not require any sort of contact between two objects. The energy is transferred as electromagnetic waves or rays.

In Power semiconductors.
The junction temperature of a power semiconductor should never be high enough, as it could corrupt the component and may even to lead to its failure. Regardless of the efficiency at which the semiconductors switches operate with, the power dissipated to the case of the semiconductor will always be significant. The size of these power electronic components keeps getting smaller, therefore causing a high power density across the component. For that reason alone, there is ever increasing need for better ways to cool these components. Heat sink are included in the structure of the power semiconductor bloc to absorb the dissipated energy.
The heat dissipation in and out of power semiconductors goes as follow: The heat is taken away from the case of the component to the heatsink by conduction. If the heatsink incorporates liquid in its design, the heat transfer between the heatsink and the liquid surface is done through conduction. However, some heatsinks are designed to exchange heat from the heatsink to the surrounding air. This process is known as convection. Figure5 illustrates one type of heatsinks commonly referred to as fin heatsink.

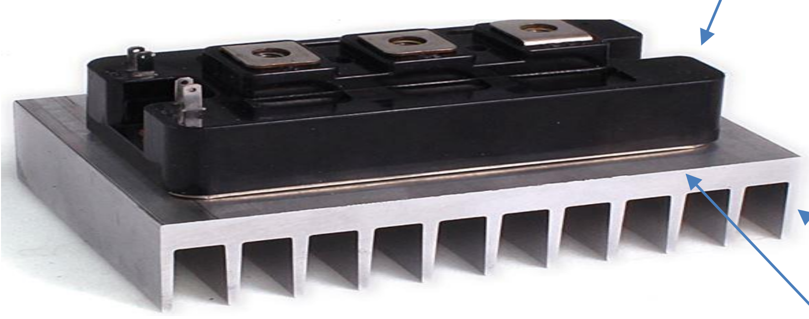

Fig5. Heatsink (modified from Eastern Voltage research [4])

On Fig5, one could see a power semiconductor mounted on top of the heatsink base. The thermal conductivity of the heatsink base is one of many factors that influence the design of a heatsink. The most common used materials for the base are copper and aluminum as they offer a high thermal conductivity. The low thermal resistance offered by these materials allows the heat to be taken away from the power semiconductors. Others critical factors to be taken into account when designing a heatsink are the space available and the cost.

Heat Transfer to and from a fin

A heatsink absorbs the heat from a semiconductor base and spreads it to the surroundings. The purpose is to relieve the semiconductor from the excess in temperature caused by power dissipated across the semiconductor device. The temperature of a semiconductor is reduced to minimum by improving the heat transfer rate between the semiconductor base and the surroundings. As shared on the previous page, the heat is transferred from the case of a semiconductor to the heatsink through conduction whereas the heat is spread from the fin to the surrounding air or liquid through convection.

The Fourier law of heat conduction states that the rate of heat transfer through a material is proportional to the area and to the negative gradient of the temperature.

$$Qx = -kA\frac{dT}{dx} \quad (1)$$

Where

Qx : Heat flux;

k: Thermal conductivity;

A: Area;

$\frac{dT}{dx}$: Temperature gradient in respect to the position x.

The negative gradient means the temperature decreases from high to low as the heat flows along position x within the material. The thermal conductivity (k) is the property of a material to conduct heat. Note that in the equation (1), the fin area was assumed to be of uniform thickness. The thermal conductivity was also assumed to be the same across the fin.

The equation below is that of convective heat transfer.

$$Qconv = hA(Ts - T\infty) \quad (2)$$

With $Qconv$: the heat transfer

h: Heat transfer coefficient;

A : The surface area;

Ts : The base temperature and $T\infty$: The temperature of the surrounding.

The heat transfer coefficient between the fin and its surrounding is thought of being the same around the fin.

From the equations above, in order to increase the rate of heat transfer, either the heat transfer coefficient and thermal conductivity would need to be increased or the surface area would have to be enlarged. Therefore, extending the base surface of a heat sink with a fin increases its surface area, which leads to a higher transfer rate.

Fin effectiveness

The fin effectiveness compares the heat transfer with and without the fin. If a fin is not present in the heatsink, the heat transfer would be done from the base to the surrounding by convection. The addition of a fin combines convection and conduction. Logically, for the fin to be considered effective, the heat transfer has to be superior to when there is no fin.

The fin effectiveness (ε) = Heat Transfer with fin/ Heat Transfer with no fin

The fin effectiveness (ε) is given by [3, 37],

$$(\varepsilon) = \sqrt{\frac{kP}{hA}} \qquad (3)$$

Where A is a cross sectional area of the fin and P the perimeter of the fin.

Going by the equation (3), for an effective heat transfer, the thermal conductivity (k) of fin material would have to be as high possible and the perimeter of the fin over the cross sectional area of the fin should be as high as possible. This is the reason why heatsink fins are usually thinner.

Multiple Fin arrays

As it can be noted on Fig5, a heatsink makes use of more than one fin; there are several fins separated by a certain distance on the base of a heatsink. Since the idea behind heat sink is to remove the heat from the semiconductor so that the device could operate safely;

The question of interest in this configuration is to know which spacing distance of fins provides optimum heat transfer rate.

It is fair to say that an increasing number of fins increase the heat transfer rate as they provides more conduction surfaces. For an optimum heat transfer in vertical fin arrays: the spacing between fins need to be equal or close to the thickness value of the fins

[3, 72]. Equalizing the spacing to the thickness is not always feasible for design practically reasons such as geometric shaping of the heatsink. Thereby leading to a tradeoff between the heat transfer and the design convenience.

Heatsink with a fan

When a power semiconductor is operated for an extended period time, a heatsink itself might become too hot, as the air surrounding gets warmer. The addition of fan forces convection by pushing away with high velocity the hot air surrounding the heatsink. Thus, increasing in the process the amount of heat carried away by the fluid in question.

Thermal resistance

Copper and Aluminum have good thermal conductivity and low thermal resistance. This is because thermal resistance is the reciprocal of the thermal conductivity. The thermal resistance of a semiconductor is ratio between temperature change and the power dissipated. The power dissipated across a semiconductor; it causes the device to heat up. The heat is transferred from the junction to the case of the semiconductor, encountering some resistance along its path. On the previous page, it was discussed how the heat flux is removed from the base of a semiconductor to the surrounding through the heatsink. In short, the thermal resistance from junction to ambient is the sum of the thermal resistance encountered from the junction to the case and the thermal resistance between the case and the surrounding. The junction to ambient thermal resistance is given by the equation (4).

$$R_{thj-A} = \frac{\Delta T}{P_d} = \frac{T_j - T_A}{P_d} \tag{4}$$

With $T_{j:}$ Junction temperature

T_A: Ambient temperature

P_d: Power dissipated

And $R_{thj\text{-}A}$: Junction to Ambient thermal resistance

$$R_{thj-A} = R_{thj-c} + R_{thc-A}; \tag{5}$$

$R_{thj\text{-}c}$: Junction to case thermal resistance while $R_{thc\text{-}A}$ is case to junction thermal resistance.

2.3 Electric Drives

An electric drive is an electromechanical system that enables to control electric motors to the specific user requirements, thus improving the overall efficiency. The electric drive makes it easy to control the speed and the torque delivered to the load application. Fig6 illustrates a simplified structure of an electric drive.

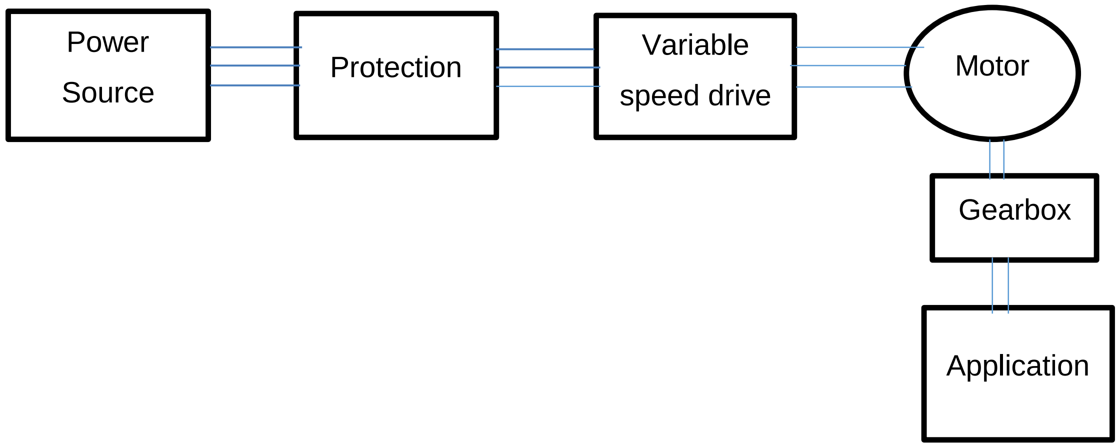

Fig6. Structure of a three phase electric drive

The protection circuitry serves to protect the system from various situations that might occur such as overvoltage, overcurrent, overheating and other circumstances. Variable speed consist of power electronic switches. The switches transfer the suitable energy to the motor form the power supply with minimum losses. The following subchapters discuss in detail the role of switches inside a variable speed drive, as well as the operation of electric motors. The energy flowing to the motor, allows it to set the load in motion. The mechanical device attached to the motor shaft is commonly referred to as a gearbox. The gearbox reduces the speed of the input motor shaft in order to provide to the load application a lower rotational speed with higher torque depending on the gear ratio of the gearbox. The gear ratio simply characterizes an inversely proportional relationship between the rotational speed and the electromagnetic torque of a motor.

2.4 Frequency converter

A frequency converter has been proven as means to optimize energy in many industries. A variable frequency converter of some sort is needed in order to control the rotational speed of a three-phase induction motor. A frequency converter varies the frequency of the ac power and in turn the speed of a motor. As highlighted on Fig7, frequency converters are classified in two categories depending on the way they realize AC-AC conversion.

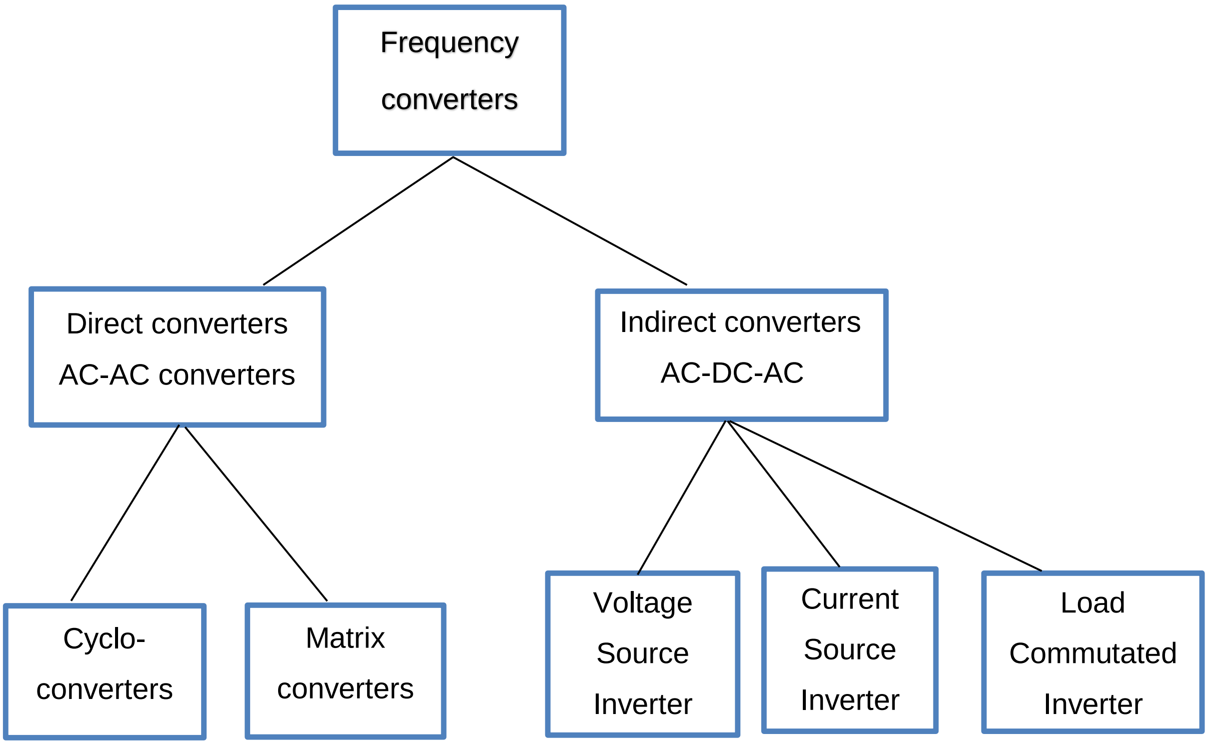

Fig7. Frequency Converter topology

A frequency converter is direct if its topology doesn't contain a DC storage elements.
In this category, the frequency converter goes from an AC power of one frequency to an AC power of another frequency without an intermediary dc link.
A cycloconverter is a direct AC-AC converter that synthesizes an AC output waveform from the segments of an AC input waveform.
The output frequency by a cycloconverter is adjustable and it is lower than the input frequency. Commutation in power semiconductor is simply the process of turning-off a semiconductor whereby the load current is relegated to the freewheeling diode.

Natural commutated cycloconverter is a cycloconverter whose power switches are commutated naturally, while a forced commutated cycloconverter is when the current in power switches is reduced below the holding current by some means of active or passive components.

A matrix converter is a forced commutated direct frequency converter, if capable of delivering an AC power at the output whose frequency and voltage could be varied. The circuit of a matrix direct frequency converter utilizes bi-directional power switches, as they are able to conduct currents and to block voltages in both polarities. A three phase direct matrix converter uses nine-bi-directional switches.

An indirect frequency converter realizes AC-AC conversion with a dc link in between. An indirect frequency converter has to have: a rectifier circuit, a dc bus and an inverter circuitry. Inverters are classified as Voltage Source Inverter or Current Source Inverter. A voltage source inverter (VSI) is a DC-AC inverter that requires a stiff DC voltage input so that it could deliver an AC voltage waveform that is independent of the load [5, 191]. A stiff DC input is usually obtained by placing a large capacitor at the DC input side. A current source inverter takes a stiff DC current input and produces a current output waveform that is independent of load parameters.

A load commutated inverter is a DC-AC inverter that utilizes SCR thyristors to produce an AC of variable frequency and voltage. The SCRs of the load commutated inverter are commutated by load voltage of leading power factor [6]. Fig8 illustrates an example of an indirect frequency converter with VSI inverter.

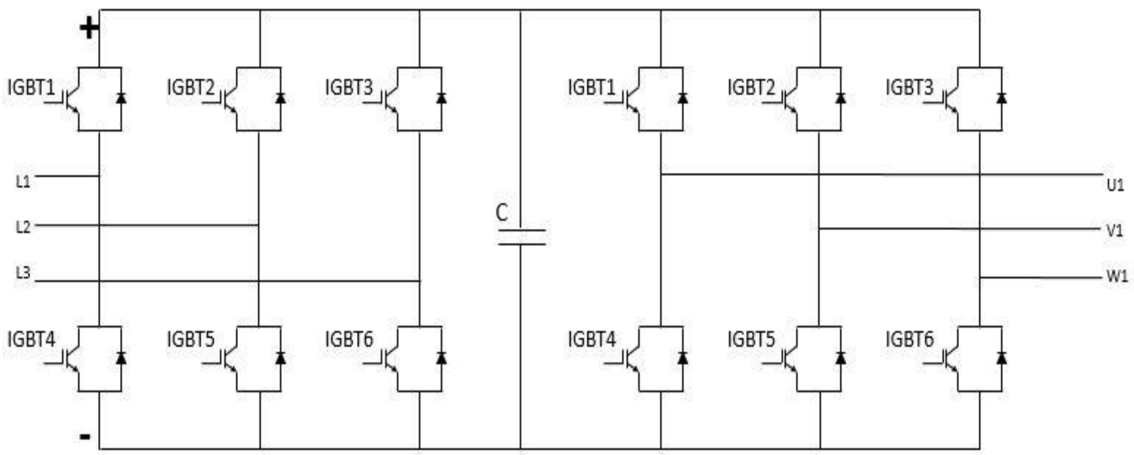

Fig8. Internal parts of an indirect frequency converter with VSI inverter.

A three phase AC power is used to power and to control the speed of a three phase induction motor. It clearly displays a rectifier, DC bus and an inverter.

The three phase full wave rectifier or bridge diodes, converts a three phase fixed frequency AC power into a DC voltage that is fed to the DC bus. The DC bus is made of capacitors and inductors. The idea is to filter the ripple voltage or in other words the ac content of the dc voltage.

It is important to mention that some DC buses uses filters for the removal or the reduction of harmonic distortion. Once the DC voltage is rid of the ripple, it is fed to the DC side of a three phase inverter. The inverter uses high switching components such as IGBTs and MOSFETs. A three-phase inverter utilizes three pairs of high switching power semiconductors. The controllable three phase AC voltage produced by the inverter is used to run the induction motor. Inverters uses modulation techniques to produce the desired switching pattern.

Pulse width Modulation

The PWM inverter realizes an AC voltage of variable magnitude in both voltage and frequency. Sine-triangle PWM is one type of PWM techniques. The output of a sine-triangle PWM is a series of rectangular trains resembling a sine wave and whose average value is close to that of sine wave, the result is then read by comparator in terms of 0s and 1s. As it can be noted on Fig9, the PWM compares a triangle waveform to a desired output waveform sine wave (reference voltage).

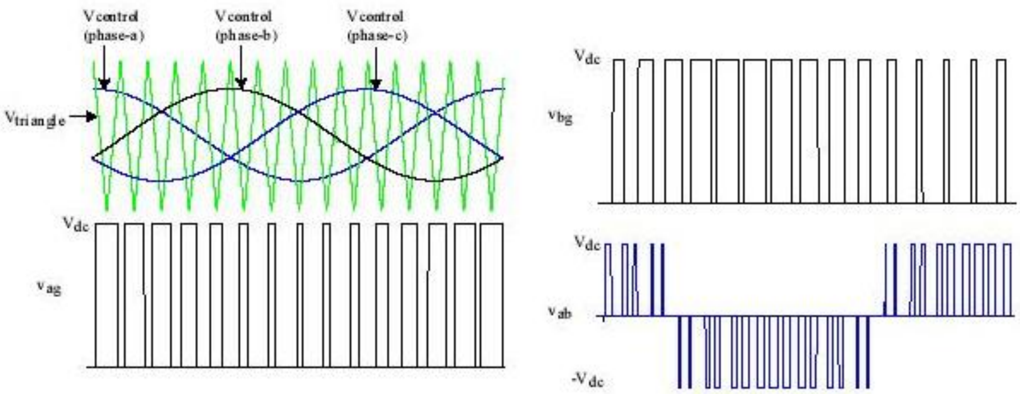

Fig9. Pulse Width Modulation (copied from Institute of Electrical and Electronics engineer Association [7])

The PWM would then use the obtained signal (rectangular pulses) to control the switches connected to the DC bus, and theses switches would then replicate the pattern at an appropriate voltage. The amplitude of the inverter output voltages can be adjusted, by simply adjusting the amplitude of the reference sinewave voltage.

Pulse Amplitude Modulation

Pulse amplitude modulation is another modulation technique used by some inverters to create a switching pattern. Unlike Pulse width modulation technique whereby the width is modified, in pulse amplitude modulation only the amplitude is modified to form a reference waveform sinewave.

2.5 Electric Motors

An electric motor is a machine that converts an electrical power into mechanical power. DC motor converts a DC electrical power into mechanical power while an AC motor is a machine that is excited by AC power in order to provide mechanical power. Both AC and DC motors can be classified even further as suggested on Fig10.

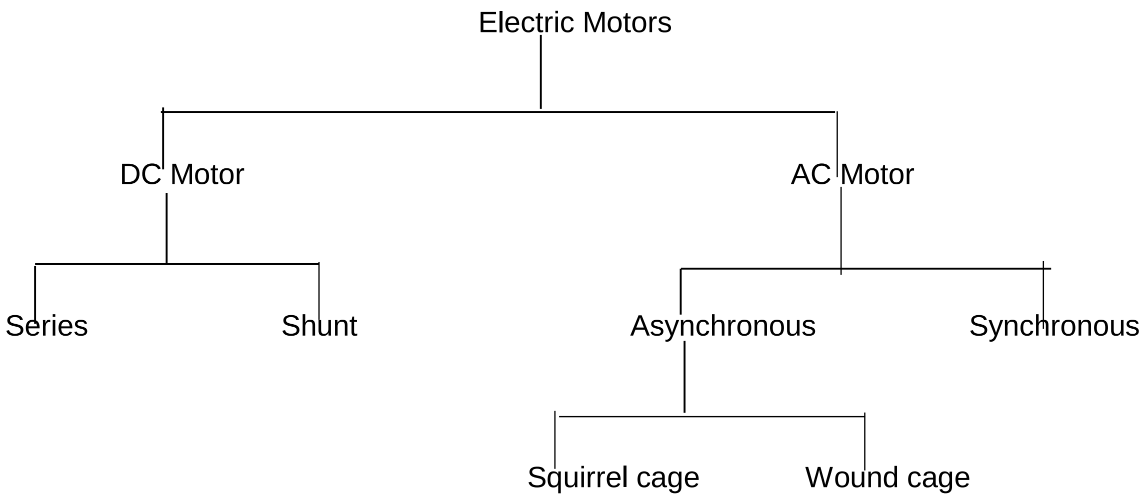

Fig10. Classification of Electric Motors

Operation of DC motor

DC motor design contains a stator and a rotating part known as the armature. The armature is a loop coil or a set of loop coils. The stator provides a constant magnetic field. The stator of a DC motor could be a permanent magnet pole or an electromagnet depending on the DC power needed by the application. The armature is connected to a DC power supply through a pair of commutator rings. When the armature is made of many loop coils, more commutator rings are added. The DC power causes the current to flow through the coil. By Lorenz law the current flowing through the coil in a magnetic field, would experiences an electromagnetic force. The magnetic force would cause the coil to rotate. Note that the field coil of an electromagnet is powered from the same DC source with the armature. When the field coil is connected in parallel with the rotor windings, the DC motor is called a shunt motor. A series motor is when they are connected in series. A shunt motor has a low starting torque but the speed of motor drops slowly regardless of the load. While a series motor has a high starting torque, its speed drops considerably with the load.

A synchronous motor is an AC motor whose rotor runs at the same of speed with the stator rotating magnetic field. A DC power excites the field of the rotor and making it to act as an electromagnet. Once excited the poles of the electromagnet are locked with the poles of the rotating magnetic field. A prime mover in the form of mechanical input is needed in order to start the synchronous motor. On the hand, an asynchronous motor always run at a speed below the synchronous speed and it is a self-starting motor. The two types of an asynchronous motor are a one phase and a three phase depending on the number of the input supply to the stator windings.

Three Phase AC Induction Motor

A three phase AC induction motor is the most commonly used electric motor for multiple industrial applications purpose. Here are factors explaining the popularity of the three phase ac induction motor: low cost, rugged structure, easiness to maintain, and the direct connection to the AC power. Three phase induction motors are found in two types; a squirrel cage induction motor or wound induction motor. An ac induction motor has two main components: the stator and the rotor.

The stator as the name suggests is the stationary part of an induction motor. Fig11 shows different parts of stator.

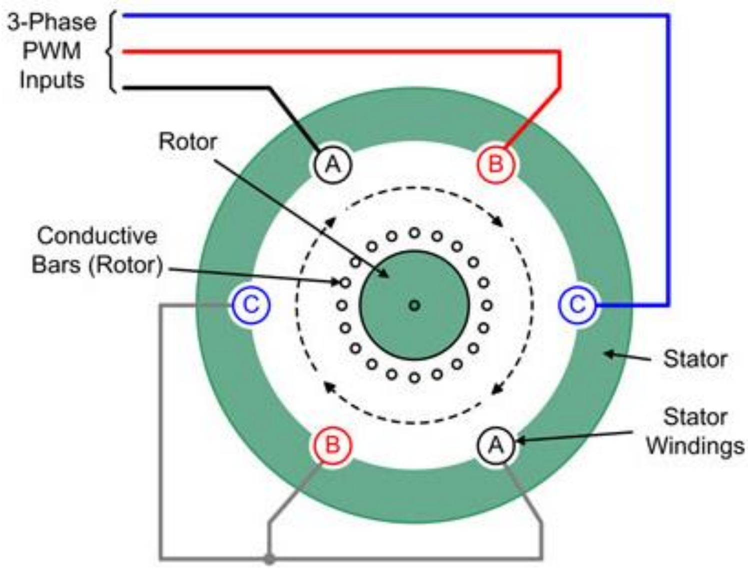

Fig11. A three phase stator and constituents (modified from Electronic design [8])

A stator contains a core, which is the protective part of a stator. The motor lamination is a thin metal sheets, and on which stator slots are found.

The whole idea behind the lamination is to reduce the power losses. Last but not the least, are the stator windings. The stator windings in a three phase motor are three individual windings, overlapping each other with a phase 120°.

These windings are attached to the slots of the laminated core of the stator. Note that a stator winding is simply a wire coil. The number of poles in an AC induction motor is determined by the evenly space bundles of wire around the stators.

The rotor is the rotating part of the motor, hence the name. Fig 12 shows various components of a rotor.

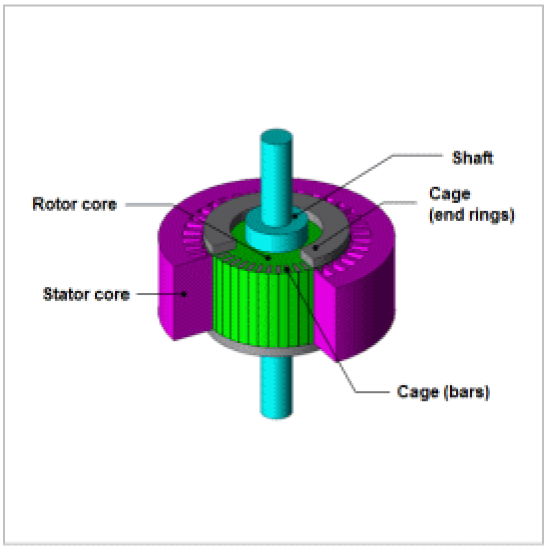

Fig12. Different parts of a rotor (copied from JMAG [9])

The rotor is made of a shaft and a squirrel cage consisting of a cylindrical rotor packaged with aluminum or copper bars that are attached together on each end by a ring in order to form a close cage. The shaft connects the rotor to a mechanical load.

Operating Principle of a Three Phase AC Induction Motor.

It is important to understand that there are no electrical connections between the rotor and the stator. They operate on the principle of electromagnetic induction.

It all starts when a three phase AC supply is connected to the three phase stator windings of an induction motor. The three phase windings behave then like electromagnets and produce three alternating magnetic fluxes also known as the net flux. The magnitude of the net flux is always constant, however the position changes in circular manner as the time goes on in a constant rotating velocity. This phenomena is called rotating magnetic field. The change in magnetic flux around the rotor, induces a current in the rotor. By Lenz law, the induced current produces its own magnetic field that opposes the change which produces it.

$$Emf = \frac{-d\phi}{\mathrm{dt}} \tag{6}$$

Emf: Induced Voltage

Φ : Magnetic flux

When a current carrying conductor is placed in a magnetic field, it experiences a force. The same goes for a rotor when it is subjected to the stator magnetic field, it creates a force, which makes the rotor rotate.

Torque and Slip of an Induction Motor

Torque is defined as a force applied to an object and which causes it to rotate instead of moving in a straight line [10, 73]. One could argue that torque is a force needed to rotate an object, it is applied to. Torque is therefore seen as a product between the force and the position vector of the object set to rotate.

$$T = r \times F \tag{7}$$

Where f stands for force; r represents the position vector and T being the torque.

In the three phase ac induction motor, the torque results from the difference between the rotating magnetic field speed and the speed rotor. That difference is referred to as the slip speed. The slip is expressed as the slip speed over the rotating magnetic field speed. The slip is usually expressed in percentage since it indicates the ratio between the slip speed and the rotating magnetic field.

$$slip\ \% = \frac{\text{rotating magnetic field speed} - \text{rotor speed}}{\text{rotating magnetic field speed}} \times 100 \tag{8}$$

Thus, when the motor starts to rotate, the slip is at 100%, only to decrease when the rotor starts to turn.

Three-Phase AC Induction Motor Used as a Generator

The operating principle of an induction generator is the reverse process of that of an induction motor. While an induction motor converts an electrical energy into mechanical energy, an induction generator converts mechanical energy into electrical one. In order to run an AC induction motor, an AC power has to be supplied to the stator windings of the motor. For the generator to start operating, it has to be excited by a mechanical force also known as a prime mover. The prime mover is anything that would provide the torque

needed to launch the generator. An example would be for example an engine, or induction motor. When operating as an induction motor, the ever changing, rotating magnetic field produced by the stator windings induces a current in the rotor. As a result, this current will lead to a rotor rotating in the direction of the rotating stator magnetic field. The rotor never reaches the speed of the rotating magnetic field. The rotor speed is always lower than the synchronous speed.
The same induction motor would operate as a generator, if by some means of mechanical commutation is made to run above the synchronous speed. Note that, when speaking of induction generator, it means that the rotor's speed is higher than the synchronous speed. Other than a mechanical excitation, a reactive power could be used to set the motor into a generating mode. Meaning; the induction cannot generate electrical power as a standalone. Induction generators are found in applications where simplicity, low cost and low maintenance are required.

2.6 Thermocouple Theory

A thermocouple is a temperature sensor. One creates a thermocouple by joining together two wires made of different metals. The two wires legs are knitted together to create a junction. The measurement junction is the point of interest. Fig13 illustrates the concept of thermocouple.

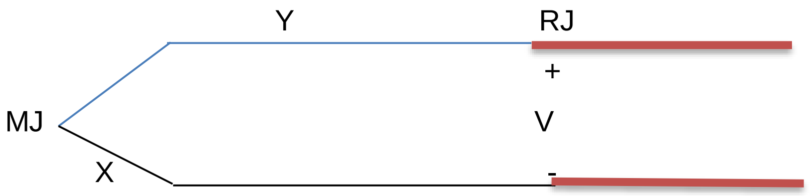

Fig13. Thermocouple

MJ stands for measurement junction and RJ is simply the reference junction. The idea behind the thermocouple theory dates back to 19th century and it came to be known as the Seebeck effect [11], named after the scientist Thomas Seebeck. The Seebeck effect happens when dissimilar metals (X and Y) as in Fig13, with junctions at different temperatures such as (MJ and RJ) would produce a voltage when heated at junction MJ.

For the same heat applied to the junction, the two metal alloys produce slightly different voltages. The voltage read at the reference junction of a thermocouple is a voltage difference between two metal wires (X and Y). The setup on Fig13 could only indicate the differential voltage between the hot and cold ends of a thermocouple (MJ and RJ), not the actual temperature. To get the actual temperature, one could refer to the thermocouple reference table which gives an indication as to which temperature is represented by which differential voltage. All thermocouple data logger incorporates thermocouple reference table, in order to display instant temperature.

Types of thermocouple

There are various types of thermocouples. Each with its particular specifications in terms of temperature range, chemical resistance and application computability, and durability [12].There are up to eight thermocouple types represented by letter J, K, E, T, N, B, S and R.

3 METHODOLOGY

The following experiment was carefully crafted in order to understand the heating up process of an IGBT in a regenerative system. Regenerative system being a system wherein some proportion of power is returned back to the system. Regenerative systems are being currently employed in many applications such as electric cars, trains, and many more.

The point behind the lab was to have a platform that could enable us to see various hotspots of different components inside a frequency converter, especially the IGBT module. Due to power dissipated under operation, power modules like an IGBT experience an increase in temperature. This increase in temperature, if not properly dealt with, could cause thermal stress to the component. The thermal stress is likely to affect the aging of the component, as well as performance degradation. Logically, one could assume that the more energy dissipated in the system, the more the components' temperature would rise.

For the purpose of increasing the power of an AC drive; a generator ran by a second AC drive, was connected to the motor in order to recoup the energy that would have been otherwise lost. For a complete picture of the lab setup and connections, refer to the appendices of this study. As highlighted above, a generator converts mechanical energy into electrical energy when stimulated. Thus, one could be able to observe the effect of negative torque applied to brake the motor on the IGBT's temperature.

In the grand scheme of the experiment, the first AC drive runs the motor in the system, while the motor is connected to the generator, which is attached to the second AC drive. This second AC drive is the one that provides the negative torque needed to brake the motor. The DC bus of the second drive is linked with the DC bus of the first ac drive.

This configuration permits the system to return the energy back to the AC line. Figure15 displays the circuitry involved in the configuration of the lab as described in this page.

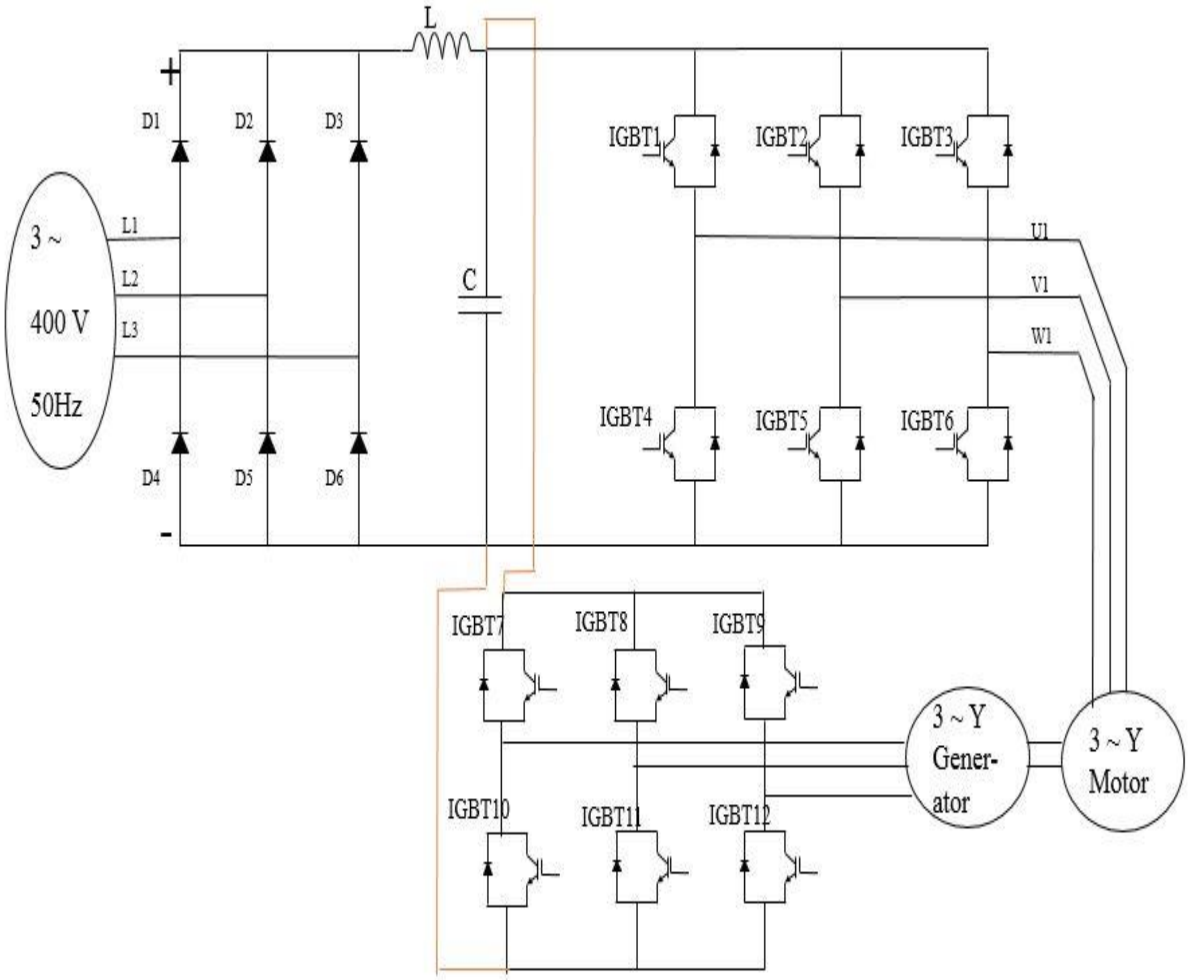

Fig14. Schematic representing the circuit of the lab

A three phase 400 VAC of fixed frequency equivalent to 50 Hz is supplied to the input terminals of a frequency converter. The 400 VAC is fed to the input terminals of a three phase full wave rectifier, consisting of three pairs of power diodes. The diodes convert the AC of 50 Hz into DC.

The DC voltage gained at the DC bus is then fed to the input terminals of an inverter. Note that the inverter in this case consists of six IGBTs. The inverter unit of a frequency converter turn a DC of known magnitude into AC voltage whose frequency and voltage could be changed. The output of the inverter bloc is used to power the three phase motor M1. The rotation speed of the rotor is proportionally linked to the frequency of the inverter output.

The generator recovers the mechanical energy from the motor and converts it back to electrical energy. It is worth to mention that the electrical energy recouped by the generator is in the AC form.

Regenerative converter

The generator M2 is producing electrical energy, but that energy need to be taken away from it. This is done in a bid to avoid overvoltage to the generator. The regenerative rectifier is converting the ac power produced by generator into DC that could be stored at the common DC Bus. The AC power produced by the generator is the product of the torque and the angular velocity.

Diodes are primarily used in many conventional rectifiers, as they are cheap, robust, and reliable and etc. There exists some drawbacks associated with diodes rectifiers. One of those is a heavily distorted current input. If the power is to be regenerated back to the AC line, there can't be no significant harmonics in the power line. The IGBTs are bidirectional power switches, as opposed to diodes which are unidirectional. The regenerative converter uses a technique known as PWM to force commutation of IGBTs. Thus, allowing IGBTs to act both as inverter or rectifier. As a result, there is a low harmonic distortion of the line current, as well as providing stability to the DC link or DC bus.

4 EQUIPMENT

This part looks into various components and equipment used in implementing the laboratory work for the thesis. This chapter will get into specifics, as well as highlighting the apparatus' relevance to the data collection.

This part looks into various components and equipment used in implementing the laboratory work for the thesis. This chapter will get into specifics, as well as highlighting the apparatus' relevance to the data collection. Two frequency converters were employed in the lab and they are joined together at the DC bus. The three phase induction motor is attached to the three phase induction generator. The three phase AC utility line feeds the frequency converter. A three phase AC power of controlled frequency exited the first frequency converter towards the motor. The output of the generator enters the second frequency converter to be transformed from AC to DC power. With a data logger and thermocouples, various hotspots inside the first frequency converter were recorded.

4.1 ACS880 Frequency Converter

In the lab, an ACS880 was the frequency converter used to control the speed of the three phase induction motor. An ACS880 is an AC drive made by ABB for AC motors. It is designed to be compatible with all kind of processes. The ACS880 is currently being used in many applications such as oil and gas, mining, metals, many more [13].
Fig15 shows the inside of an ACS880 module.

Fig15. ACS880 module (copied from acs880 manual [13])

The ACS880 is voltage fed frequency converter, the torque of the ac motor was controlled by the direct torque control method. The two ACS880 that were used in this study, one had power rating of 3.2kW while the other was capable of handling up to 7.5kW. The IGBT supply units in ACS880, when operated in regenerative mode could convert a three AC voltage into a DC voltage. The ACS880 is embedded with du/dt filters that are there to suppress the voltage spikes coming out the inverter output. Moreover, the filters are there to eliminate the capacitive leakage currents, and the frequency losses and frequency emission associated with the motor cable [13]. Table1 refers to key technical data of the ACS880.

Table1. AC drives used in the lab.

AC drive (I) ACS880-01		AC drive (II) ACS880-01	
Power Rating	3kW	Power Rating	7.5kW
Current Rating	7.2A	Current Rating	17A
Efficiency	98%	Efficiency	98%

4.2 Motor M3AA100LD-4

The investigation question was about the heating of the inverter module of a frequency converter. Frequency converters are used to run and control the speed of motors. Thereby, the whole experiment was designed in order to observe the change in internal energy of the inverter while it is running an AC induction motor.
The type of motor connected to the ACS880 is a 3~Motor M3AA100LD-4 3~Motor M3AA100LD-4 is a three phase 4 pole induction motor fitted with PTC thermistors[14]. Table2 summarizes the electrical and physical characteristics of M3AA100LD-4 as written on the nameplate.

Table2. Handling Power capabilities of M3AA100LD-4

Power Ratings	3 kW
Voltage Ratings	3~ Y 400V
Physical Properties	PTC with thermistors
Protection Rating	IP65
Maximum Rotational Speed	2000 rpm
Efficiency	88%
Cost	400 Euros

4.3 TC-08 Data logger

A TC-08 DATALOGGER is one of the most used tool in measuring temperature ranging from minus a couple of hundred to thousands of degree Celsius. TC-08 could record eights measurements simultaneously through its eight input channels. [15]

Features of a TC-08 DATALOGGER

- Operates with virtually all types of thermocouples
- Flexible and moveable, as it draws its power supply from PC USB port.
- It comes with USB interface
- Range (-270° to +1820°C)
- Availability of 8 input channels.
- Could record up to 10 samples per second.

4.4 J-type thermocouples

The connectors of the thermocouples in the course of the lab were miniatures ones with ANSI PLUG. The connectors are calibrated J-type. Table3 below displays properties of J-type thermocouple [16].

Table3. J-type thermocouple properties

J-type Thermocouples	
Metallic composition	Iron Constantan
Curie Temperature	+770C
Practical range	-40C to +750C
Tolerance	±2.2C

5 Measurements

5.1 Data Collection

The current chapter displays and analyzes the data collected in the laboratory in relation to the thesis topic. Using the AC drive control panel, a motor was started at a speed of 500 rpm for a duration of seven minutes. After that brief interval, the AC regenerative drive was launched to deliver braking torque to the generator connected to the motor. By doing so, one could observe the heating process of an IGBT module with and without the generator. Fig16 displays the temperature over time of different components inside the AC drive.

5.1.1 500 rpm braked at a 100% torque

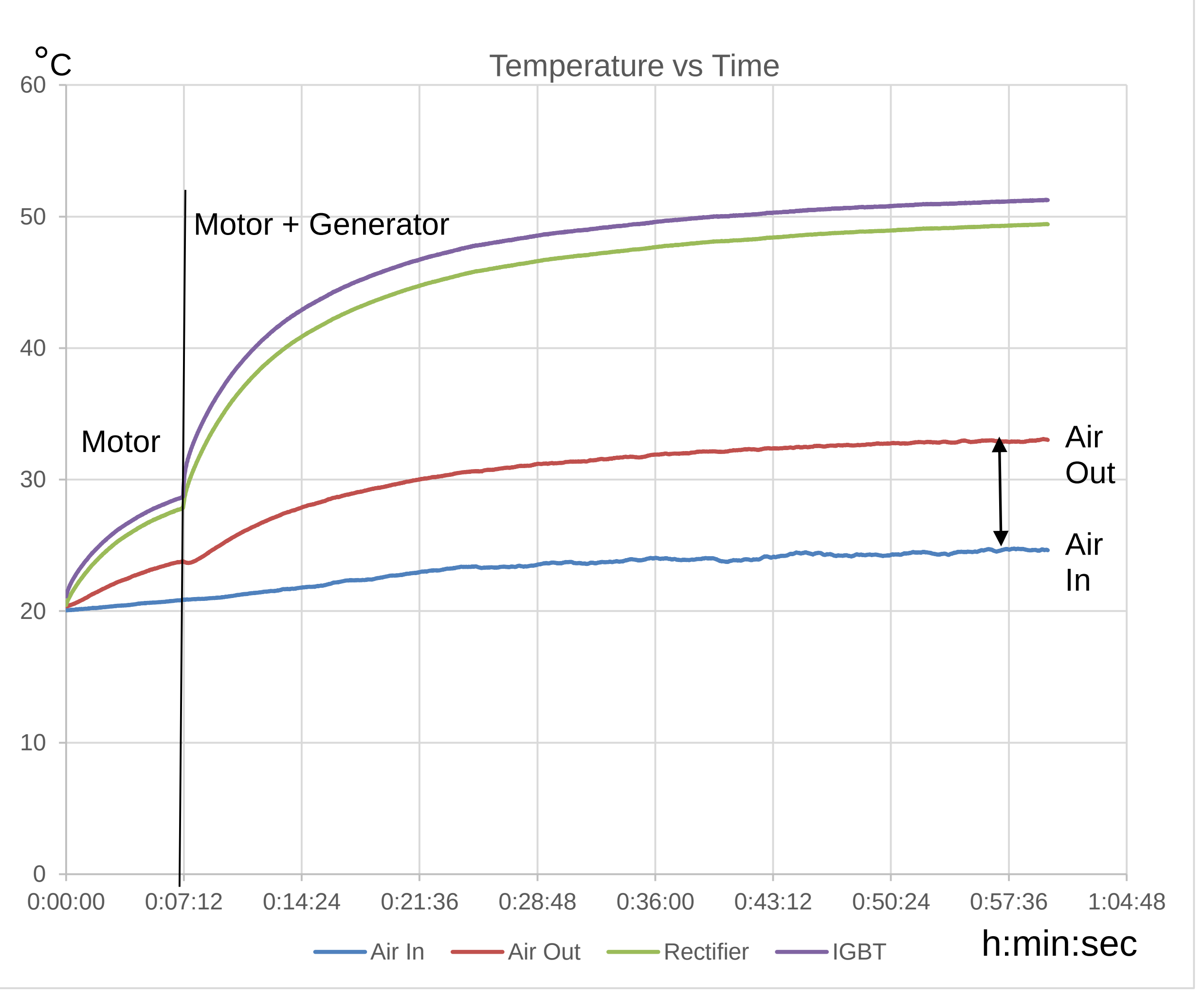

Fig16. Temperature vs time chart, 500 rpm and 100%

Inside the first 7 minutes, only the motor was running at 500 rpm. By observing Fig16, one notices a certain bend on the IGBT and rectifier curves at 490 sec. The bend corresponds to the time when the generator was set in motion. From that point, the generator started recovering mechanical energy from the motor.

5.1.2 500 rpm braked at 70 and 100% torque

Similarly to 7.1.1, the motor was started at 500 rpm for about 7minutes. Unlike 7.1.1, the torque wasn’t applied at 100% right away. After 7 minutes of motoring, the torque to generator was 70% and then 100%. This is done in the effort to understand the effect of a changing braking torque on the temperature of an IGBT. Fig17 highlights the measurements obtained.

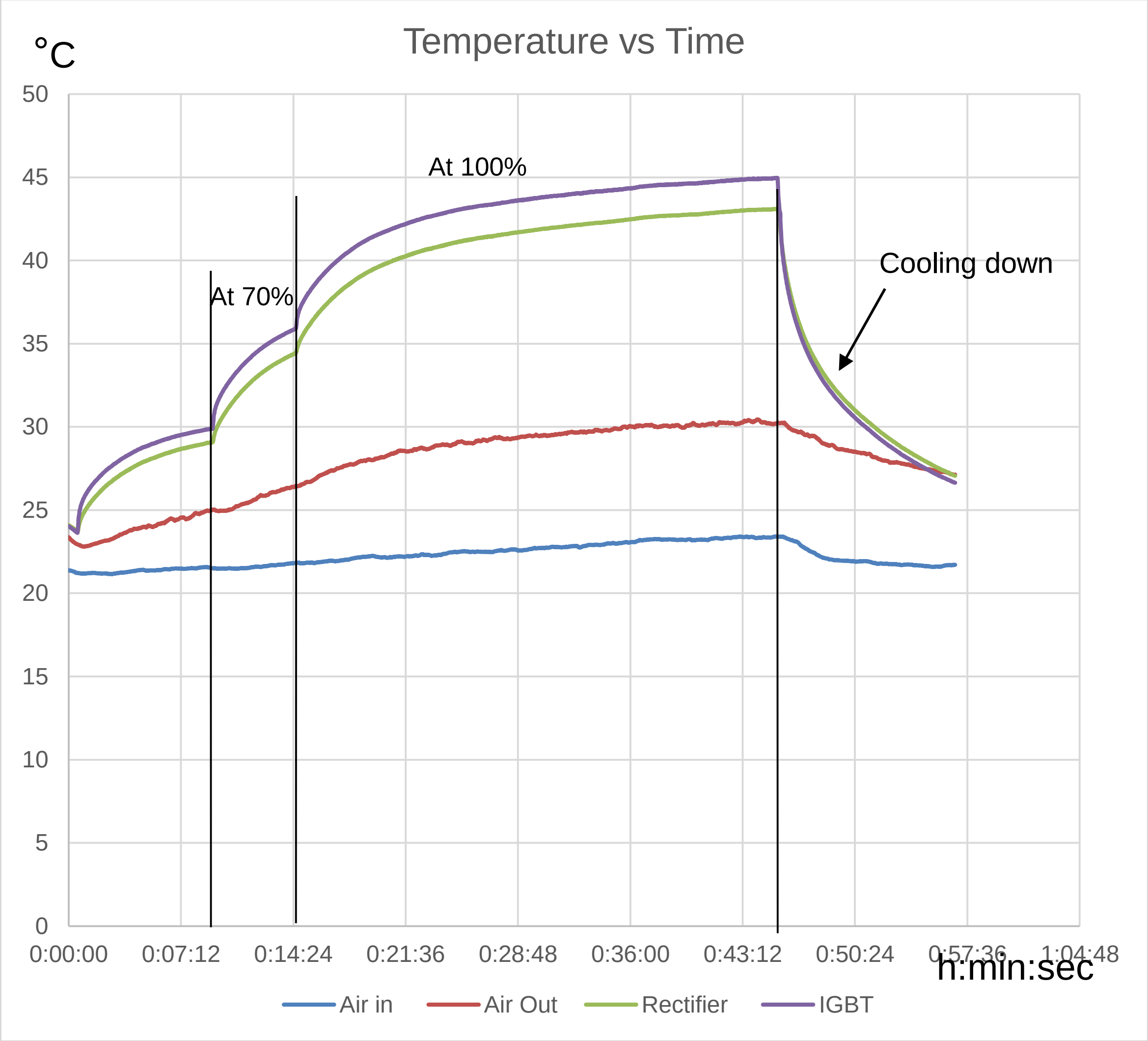

Fig 17. Temperature vs time, at 70% and at 100%

From Fig17, the temperature of the power electronics components inside the ac drive rise really fast. After 40 minutes or 2400 sec, the power was switched off and the system was stopped. The temperature of the power components dropped really fast during cooling off time. The curves highlights the heating process power semiconductors during operation.

5.1.3 1000 rpm braked at 70%

The motor was started at 1000 rpm. After 7 minutes, through the ac regenerative drive control panel, a torque was applied at 70% to brake the motor. The temperature versus time curves are represented on Fig18.

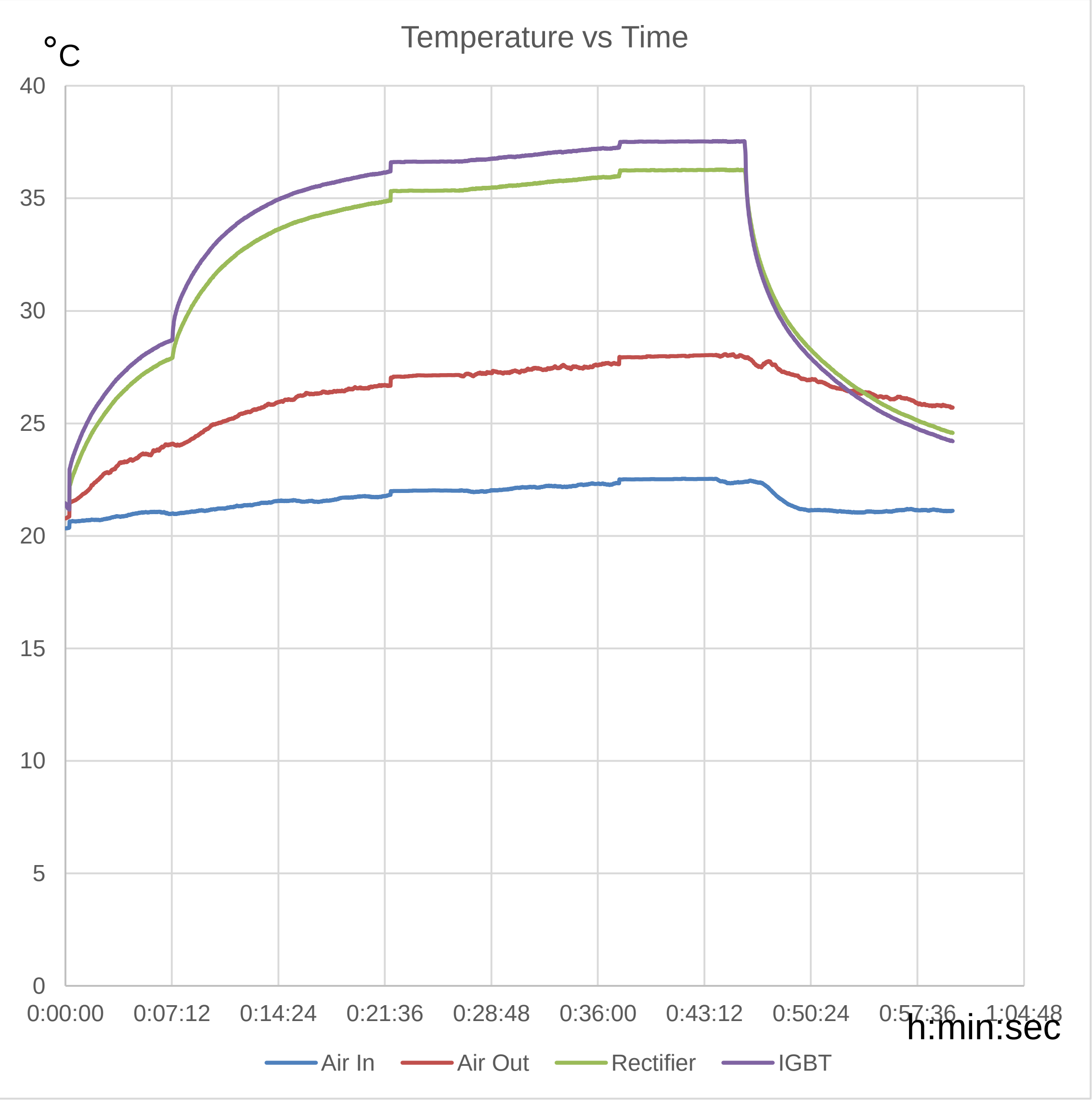

Fig18. Temperature vs time, 1000 rpm at 70%

With 40 minutes past, the system was switched off. From there on, the graph shows the cooling down process of power semiconductor components inside the AC drive.

5.2 Analysis

5.2.1 500 rpm braked with 100% torque

In this part, the raw data obtained from measurements would be processed and analyzed in relation to the investigation topic. Fig19 displays the IGBT temperature sensed by the data logger over the displayed period of time. Fig19 also shows the temperature of incoming air at all times during test measurements.

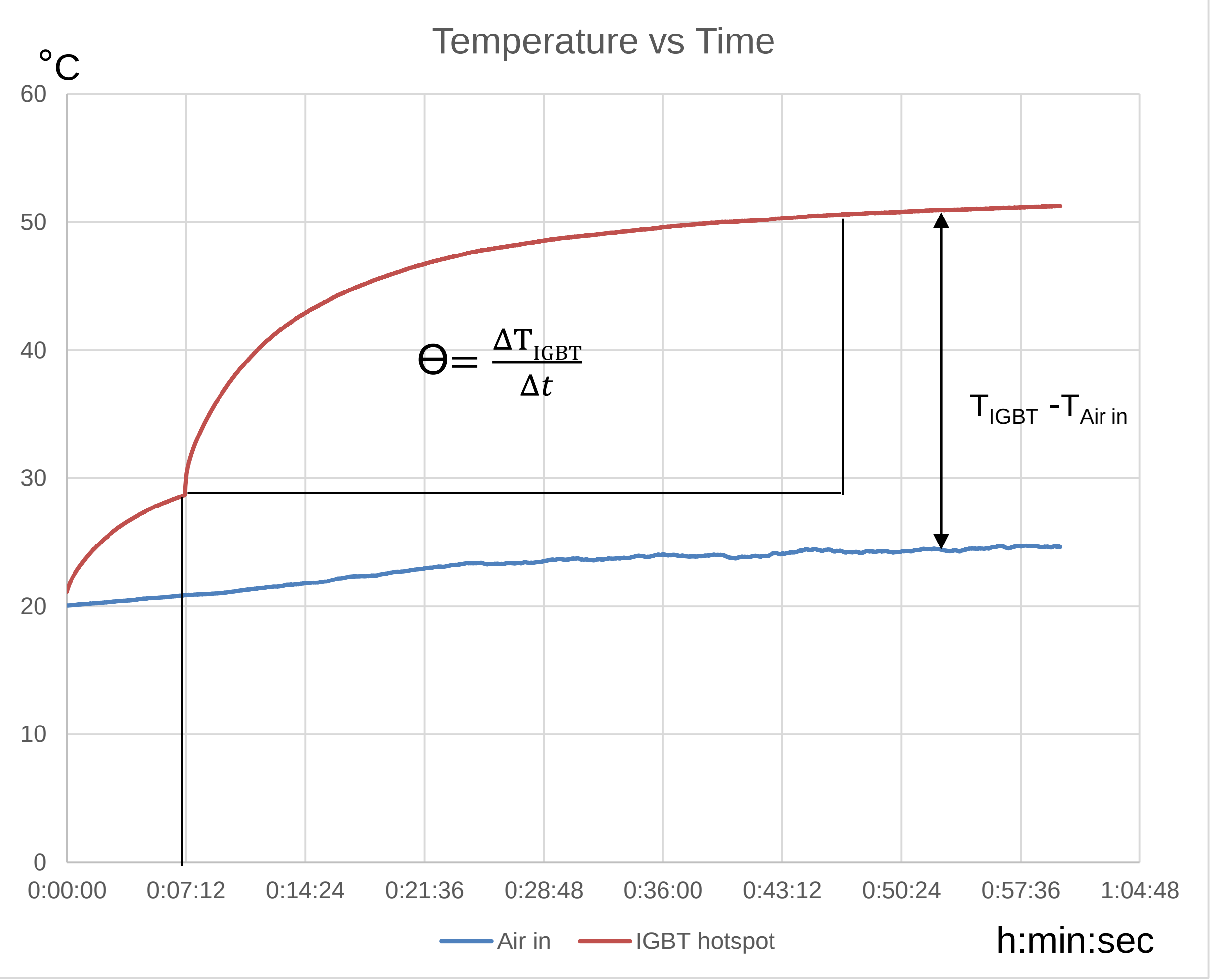

Fig19. Thermal Response of 500rpm at 100% torque.

The motor was ran at a 500 rpm for 7 minutes. Note that during this period of time, the generator and the regenerative drive were in standby mode. After 7 minutes, the generator was given a torque of 100% through the regenerative drive control panel.

As discussed in the theoretical part of this study, IGBTS heat up during their operation. The junction temperature of an IGBT increase with the power dissipated across it.

Therefore, the ascendance of the curve representing the IGBT temperature corroborates with the theory.

From time (t) t = 0 sec to t = 490 sec;

The temperature (T) increased from T = 21°C to T = 28, 6°C

The rate (ϴ) at which the temperature of the IGBT was rising at

$$\theta = \frac{28{,}6℃ - 21℃}{490} = 0{,}028℃ / \sec = 0{,}96℃ / \min \quad (9)$$

With each minute passing by, during the first 7; the IGBT was heating up by 0,96°C per minute. As discussed in the theoretical chapter, a heatsink alleviates the heat incurred by the IGBT during operation. Given the fact that there is a heatsink inside the AC drive; it means the IGBT was picking up heat at even faster rate than θ , only to be reduced by the heat exchange between the IGBT and heating sink and the ambient temperature. Clearly, the rate θ reaffirms the heating problem posed by power components such as IGBT during use.

After 7 minutes of operation, the generator was kicked into action by applying 100% torque from the second AC drive. By observing Fig 20, one notices that the temperature of the IGBT kept rising until it became steady. The IGBT curve goes into steady state around t = 50 min, after which the temperature no longer increased by much.

The thermal response of the IGBT (ϴ) from t = 7min is given by,

$$\Theta = \frac{\Delta T_{IGBT}}{\Delta t} = \frac{50{,}13 - 28{,}6}{3600 - 490} = 0{,}007°C \,/\, \sec = 0{,}42°C \,/\, min \quad (10)$$

This value gives a clear picture as it describes the rise in temperature of the IGBT in the entire time the generator was part of the system. By knowing the steady state temperature of the IGBT as well as the ambient temperature, the thermal resistance of the IGBT module could be calculated from the formula below;

$$R_{thj-A} = \frac{T_{IGBT} - T_{Air\ in}}{Pd} \quad (11)$$

R_{thj-A}: Thermal resistance.

T_{IGBT}- $T_{Air\ in}$: The steady state temperature of the IGBT minus the ambient temperature.

P_d: Power dissipated.

The thermal impedance of an IGBT is key since it indicates the thermal behavior of a particular type of IGBT. When calculating thermal resistance from the experiment measurement as it is the case here, one has to wait until the temperature of the IGBT has reached a steady state.

The efficiency of the frequency converter (ACS880-01) as indicated in the ABB manual [12], it is said to be 98%. This implies a 2% power dissipated across the frequency converter. Thereby, the power dissipated is 2% of the rated power. The rated power of the first frequency converter is given by Table1 as 3kW.

$$\mathrm{P_d} = \frac{3\mathrm{kW}.2}{100} = 60\mathrm{W} \qquad (12)$$

Note that for the sake of simplifying the calculation, the totality of power dissipated was assumed to be lost across the IGBT module. In reality, some power was dissipated across the rectifier circuitry inside the AC drive.

The thermal resistance of the IGBT ($R_{thj\text{-}A}$) in the system when the motor is running at 500 rpm and braked with 100% torque.

$$\mathrm{R_{thj-A}} = \frac{50{,}13℃-28{,}6℃}{60\mathrm{W}} = 0{,}36℃\ /\ \mathrm{W} \qquad (13)$$

A mere 0,36℃ / W is a low value for thermal impedance, as it implies for a very 1W dissipated across the IGBT, its temperature increases only by 0,36℃. A good heatsink of the IGBT module in the system would go a long way to explain this low thermal impedance value.

Table 4 and Table 5 below display currents, voltages and power read across the system during operation.

Table4. Readings during the first 7 minutes.

AC drive readings during the first 7 minutes of operation without the generator.	
Motor frequency	16.70Hz
Motor Current	2.74A
Motor torque	3%
DC Voltage	578V
Output voltage	138V
Output power	0.07kW

During the first 7 minutes, only the motor was running. The power supply to the drive was 3-phase 400 V supplied at 50 Hz frequency. The AC drive enabled the motor to run at 500 rpm, by reducing the frequency from 50Hz to 16,70Hz. Also, on Table 4, the output voltage is lower compared to the supplied 400V. This could be explained by the constant voltage hertz ratio. Whenever a frequency is lowered by an AC drive, the output voltage is also reduced in order to limit the current going to the motor. Because of the no load or no closed external circuit, the induction motor would develop only enough torque to overcome the friction and the winding losses. Hence the 3% motor torque.

Table5. Readings with the generator in the system.

AC drive readings From 7 minutes onwards		AC regenerative drive Readings After the 7 minutes mark	
Output frequency	18,11 Hz	Output frequency	-14,86 Hz
Motor Current	6.4 A	Generator current	6.04A
DC voltage	566V	DC voltage	566V
Output Voltage	155V	Output Voltage	111V
Output Power	1.45kW	Output Power	-0.80kW

After 7 minutes, an electromagnetic torque was applied to the generator. In this part, the generator is connected to the motor. The torque would act as a counter torque to the mechanical torque produced by the motor. Therefore, the mechanical torque from the motor has to overcome this counter torque in order for the generator to convert mechanical energy into electrical energy. A higher percentage of torque to the generator leads to a higher electrical power output. On Table 5, the sign difference between the input power of a motor and output power of generator is notable. The sign is there to indicate the direction of the power flow. Looking at Table 5, the voltage and current read by the regenerative drive are lower compared to the voltage and current read at the first ac drive. This could be explained by the conversion losses. In converting mechanical energy back to electrical form, some energy were dissipated in the form of heat.

The torque (T) used to brake the motor could be calculated from the readings of Table5.

$$T = \frac{\mathrm{P}}{\omega} = \frac{P\,.\,60}{\mathrm{rpm.2\pi}} \tag{14}$$

Where P: Power; ω: angular frequency; and rpm: revolutions per minute of the motor.

$$T = \frac{1450\ \mathrm{W.60\ Hz}}{500\ \mathrm{rpm.2\pi}} = 27{,}7\ Nm \tag{15}$$

5.2.2 Comparison between Fig16 and Fig18

In this section, The IGBT thermal response curve on Fig 16 was compared to the one on Fig18. On Fig16, the motor was running at 500 rpm and it was braked with a 100% torque whereas on Fig18, the motor was running with the speed of 1000 rpm with a 70% torque.

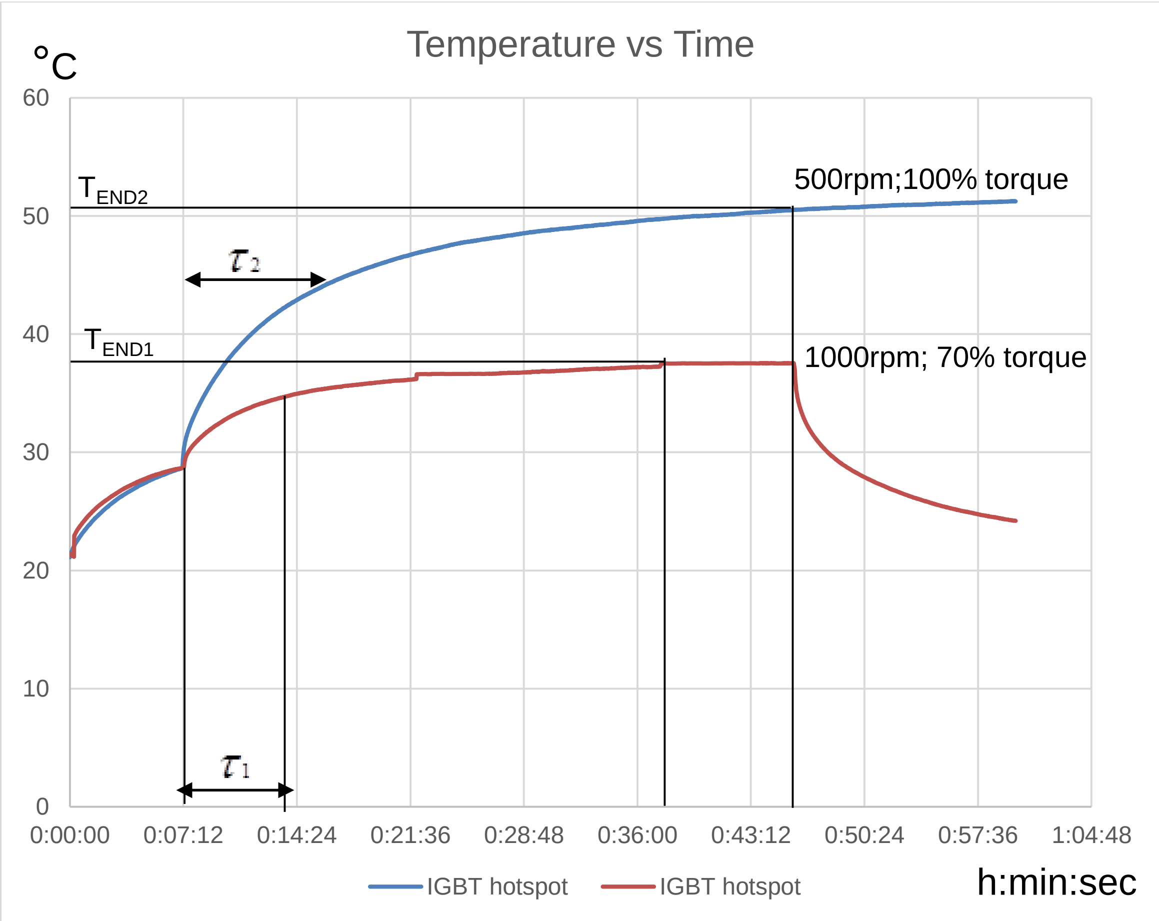

Fig20. Comparison of Fig16 and Fig18

Up to 7 min, the system operated the motor without the generator. By looking closely at the two curves on Fig20; the IGBT was picking up the heat almost at the same rate in both cases.

Going by the shape of both curves from time t = 490 sec to t=2742 sec; one could approximate the curves with an equation of the form;

$$T = ke^{\frac{-\tau}{t}} \tag{16}$$

Whereby T is the temperature of an IGBT

k: the thermal response coefficient

τ: the time constant

t: the time variable

Going by Fig20, the saturation temperature of the 70% torque curve (T_{END1}) is equal to 38°C and the saturation temperature (T_{END2}) of the 100% torque curve is 51°C.

The time constant (τ_2) of the 100% torque curve is approximately 340 sec

The time constant (τ_1) of the 70% torque curve is 266 sec.

Knowing time constants (τ_1) and (τ_2); the respective thermal coefficient (k_1) and (k_2) can be deduced from formula:

$$k_1 = T_{END1}.\, e^{\frac{\tau_1}{t}} = 38°C.\, e^{\frac{266\,\text{sec}}{2742\text{sec}-490\text{sec}}} = 42{,}76°C \qquad (17)$$

$$k_2 = T_{END2}\,.\, e^{\frac{\tau_2}{t}} = 51°C.\, e^{\frac{340\,\text{sec}}{2742\text{sec}-490\text{sec}}} = 59{,}3°C \qquad (18)$$

5.3 Measurement Findings versus Theory

In this part of the study, measurements would be analyzed and compared through the lenses of the theory basis.

In the introductory part of this study, it was highlighted that power semiconductor devices such as an IGBT generates heat during use. The theoretical part of the study introduced the concept of the heat propagation in and outside of the IGBT module. The thermal impedance was seen to be equal to the difference between the junction and ambient temperature over the average power dissipated across the IGBT.

Fig21 shows an example of an example of a thermal impedance curve of an IGBT.

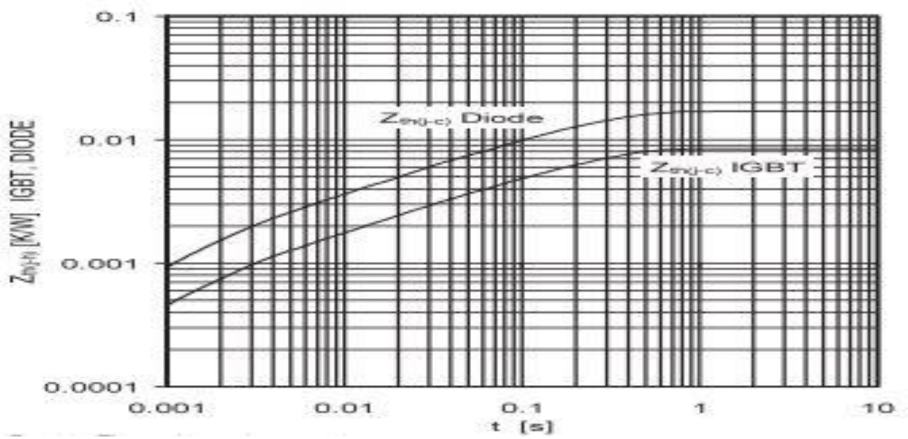

Fig21. Thermal Impedance vs time (Copied form the ABB library [16])

Fig21 displays curves of IGBT and diode thermal impedance. It clearly show that the thermal impedance increases until a steady state at which a thermal resistance is attained. By looking at measurements obtained as represented on Fig16, Fig17 and Fig18; the temperature versus time curves are similar in shape as the thermal impedance curve on Fig21. This correlates with the theory, as the thermal impedance depends on the change of the junction temperature and the power dissipated. Given a constant power dropped across the IGBT, it makes sense that the thermal impedance curve would follow the IGBT curve of temperature versus time.

The theory helps understanding the inverse exponential curve shape of the IGBT temperature versus time curve. For a temperature versus time IGBT curve to reach a thermal equilibrium state, the heat flow between two points should be the same. The two points in this case are the junction of an IGBT and the heatsink end. All the heat capacitances within the IGBT module plus the heatsink have to be thermally charged to a specific temperature, in order for the module as whole to reach steady state.

When the motor was ran at 5000 rpm and braked with a torque of 27,7Nm; the thermal resistance of the IGBT module was calculated to be around 0,36$℃ / \mathrm{W}$. This value indicates a rise in junction temperature by 0,36℃ for a watt dissipated across the module. One could argue that this value falls within the acceptable ranges of IGBT thermal resistance since a good designed IGBT must have a lower thermal resistance.

As it can be noted on Fig20, during the first 7 minutes of operation when only the motor was running, the two curves are almost one and the same. One curve displays the IGBT temperature with a motor speed of 500 rpm while the other curve displays the IGBT temperature at 1000 rpm of motor speed. The two heating curves diverge significantly once the torque was applied to brake the motor. From 7 minutes onward, the curves seem to indicate different thermal behavior of the same IGBT module when operated at different torque. An attempt to explain the present findings would go as follow, during the braking of the motor, the ac drive adjusts the motor flux and torque in order to overcome the counter torque from the generator side; in the process it increases motor current. Since the temperature of an IGBT die is associated with the power dissipated in the die, an increase in temperature is likely to change the thermal impedance of the IGBT. Thus, one could suggest that the power loss in the system is lower in the 70% torque curve than in 100% torque curve.

5.4 Efficiency of the system.

The efficiency calculation of a system is crucial, as it indicates the level of waste in a system. Thus, it could be improved upon. It is usually done by calculating the ratio of the output to the input.

In this study, an AC drive converts an AC power of one frequency into an AC power of another frequency in order to provide various speed to the induction motor at the receiving end. The output of the induction motor is in the form of mechanical energy. That energy is converted back to electrical energy by the generator connected at the output of the induction motor. Finally, the AC power is converted into DC power by a regenerative ac drive. The DC bus of the two ac drives are linked together.
The energy loss in the system is the sum of the energy lost at the AC drive, AC regenerative drive and the loss from the motor to generator energy.
The efficiency of both ac drives is assumed to be 98% as given by ABB manual. Table6 displays the values needed to calculate the efficiency from the input of the motor to the output of the generator.

Table6. Extracted from Table 5

At the input of the motor		At the output of the generator	
Current (I)	Voltage (V)	Current (I)	Voltage (V)
6,4	155	6,04	111

Motor input to generator output efficiency

$$\frac{\text{Generator output power}}{\text{Motor input power}} \times 100\% \tag{19}$$

Motor input to generator output efficiency;

$$\frac{(0{,}85).(6{,}04\,A).(111V).\sqrt{3}}{(0{,}85).(6{,}41A).(155V).\sqrt{3}} \times 100\% = 67{,}6\% \tag{20}$$

The power factor of 0,85 is deduced from the readings on Table 5.

Therefore, the overall efficiency (η) of the system is equal to 98% of 67% of 98%

$$\eta = (0{,}98).(0{,}67).(0{,}98).(100\%) = 65\% \tag{21}$$

Note that this value of efficiency is a mere estimation, The calculation of an accurate efficiency goes outside of the scope of this thesis, as the data collected during the experiment was not carried out with that intended purpose in mind.
Furthermore, the energy recouped is fed back to the common DC bus, thereby increasing the complexity of knowing the exact value of the energy returned to the system.

6 Conclusion

The goal of the thesis was to establish the heating pattern of an IGBT module in a system containing a motor and a generator. The student was already familiar with the operating principle of a three phase induction motor. This study was meant to take the familiar concept to another level, with the added generator and regenerative AC drive into the system. The importance of the work carried out lies in the fact that the concept of this thesis was set to be included on the curriculum of power electronics laboratory class.

The thermal responses of the IGBT module were recorded with varying motor speed. Also, the braking torque applied to the system was changed in order to study its effect on the overall heating of the IGBT module. The time it took to reach the steady state, as well as the magnitude of the saturation temperature were found to be dependent on the percentage of electromagnetic torque applied into the system.
Whenever the motor was set to run at a high speed, the percentage of torque applied into the system had to be reduced to a certain percentage in order to operate within the power and current ratings of the AC drive. To overcome the situation, the lab concentrated on low to mid-range speed of the motor, to which the torque percentage could be varied over a wide range.

It is fair to say that the study achieved its objectives, as the IGBT thermal responses were obtained through measurements and analyzed in relation to the topic of investigation. The study was also able to determine the thermal impedance of the IGBT module for a specific motor speed and braking torque. As for possible further investigation, one could compare the internal heating of an IGBT module inside the AC drive to that of the IGBT bloc inside the regenerative AC drive.

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Motor and Generator coupling

Fig22: Motor and generator coupling

Lab Setup

Fig23: Setup of the lab